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RESEARCH ARTICLE

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Factors affecting transpiration of *Pinus tabulaeformis* in a semi-arid region of the Loess Plateau

Abstract The effects of soil water and meteorological factors affecting transpiration of *Pinus tabulaeformis* were studied under different levels of soil water content to offer a scientific basis for increasing efforts in afforestation survival and management of soil water in forested land. Under artificial control methods for soil water and potting experiments, the transpiration rate (T_r) of *P. tabulaeformis* and environmental factors were measured using a portable steady porometer (Li-1600) and a speedy weight method (BP-3400) during a representative fine day in the growing season of 2004. The results indicated that the diurnal course of T_r and R_{st} of *P. tabulaeformis* displayed a double-peaked curve and a "W" curve under different levels of soil water content. Given a representative fine day, the T_r could be represented as a cubic relation with soil water content (SWC). The SWC which caused maximum T_r values of *P. tabulaeformis* was 17.7%, 19.8%, and 17.5% in July, August and October respectively. T_r was affected not only by physiological characteristics, but also by SWC and meteorological factors. T_r was significantly correlated with meteorological factors when the soil water was sufficient, but this correlation would decrease under conditions of serious water stress. Under such stress conditions, air temperature was the primary factor to affect T_r in July and August and photosynthetically active radiation (PAR) was the primary factor in October. When soil water is sufficient, the main factors affecting T_r were relative humidity (RH), air temperature (T_a) and leaf temperature (T_l) in July, August and October respectively.

Keywords *Pinus tabulaeformis*, transpiration characteristics, soil water content, meteorological factors, semi-arid region of Loess Plateau

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1 Introduction

Transpiration is the main method of plant water consumption, which is the most important condition in water-heat transmission of the Soil-Plant-Atmosphere-Continuum (SPAC). This is one of the key projects presently under investigation in the fields of agriculture, forestry, aerography, hydrology and bionomics. Water deficit is the major limiting factor of plant growth in the semi-arid region of the Loess Plateau (Zhou et al., 2002; Meng et al., 2005). Characteristics of plant water physiological ecology have been systematically studied (Irvine et al., 1998; Kumar et al., 2001; Lagergren et al., 2002; Li et al., 2004; Michael et al., 2004; Bu et al., 2005; Wang et al., 2005). However, transpiration is a complex process of plant physiology and water movement and is closely related to soil water and environmental factors (Guo et al., 1992; Fu et al., 1998; Yue et al., 2003; Zhang et al., 2005; Tian et al., 2005). *Pinus tabulaeformis* is a multipurpose afforestation species and the major reconstructive species in the semi-arid region of the Loess Plateau. By adopting artificial methods to control soil water and with potting experiments, the transpiration rate (T_r) of *P. tabulaeformis* and the factors affecting it were measured by a portable steady porometer (Li-1600), a speedy weight method (BP-3400) and TRIME-TDR. The relationships between transpiration of *P. tabulaeformis* and soil water, as well as with meteorological factors, were statistically analyzed with SPSS software to provide a scientific basis for enhancing afforestation survival and management of soil water in afforested lands.

2 Study area

Our study area was located at the experiment station dealing with forest runoff of Beijing Forestry University, in a semi-arid region of the Loess Plateau (37°36′58″N, 110°02′55″E) in Yukou town, Fangshan County, Shanxi Province, China. This area is a typically hilly and gully loess region at an elevation of 1200 m and is dominated by a warm temperate continental monsoon climate, with the typical characteristics of severe spring droughts in northern China. The annual mean temperature is 7.3°C and the cumulative temperature above 10°C rises up to 2223.5°C. The dryness coefficient is 1.3, while annual precipitation is 416 mm. The amount of precipitation from June to September is over 70% that of the whole year, while annual free water surface evaporation is 1857.7 mm and maximum evaporation occurs from April to June. At this time, the soil texture is an even loess soil, and the average soil bulk density is 1.20 g/cm^3.

3 Materials and methods

3.1 Materials

Cultivars of *Pinus tabulaeformis* were selected for the study. Three-year-old seedlings were selected on April 20, 2004. They were 73 cm high, with diameters at ground level being 1.28 cm. They were put into pots (29 cm diameter and 26 cm high) containing loess soil. The pine seedlings would maintain normal growth given adequate water.

Soil water of the experimental seedlings was artificially prepared using TRIME-TDR and BP-3400. Four soil water content levels of 18%–21% (I), 13%–16% (II), 9%–12% (III) and 5%–8% (IV) were applied with three replications. Treatments I, II, III, and IV represented conditions of adequate soil water, light soil water stress, medium soil water stress and severe soil water stress respectively. The pots were placed outdoors in the sun under a canopy shelter to protect them from rain. The soil water content was controlled by TRIME-TDR and BP-3400, with transpiration regulated by adding water and covering the pots with a plastic membrane. Transpiration rate (T_r), stomatal resistance (R_{st}), air temperature (T_a), leaf temperature (T_l), photosynthetically active radiation (*PAR*) and air relative humidity (*RH*) were measured by a portable steady porometer (Li-1600) and correlated with information from the nearby HOBO weather station to analyze the relation between transpiration rate and the factors which affect it on typical clear days on July 8, August 3, October 5 in 2004. At the same time, the diurnal course of T_r, R_{st} and water consumption rates of the pine seedlings were analyzed on August 3, 2004.

3.2 Methods

3.2.1 Transpiration rate

The transpiration rate of healthy leaves exposed to the sun in the middle of the seedlings were measured by a Li-1600 every other hour from 8:00 to 18:00. The average value of T_r was calculated from data collected on three stable dates.

3.2.2 Water consumption rate

The water consumption of *P. tabulaeformis* was measured by a weighting method every other hour from 6:00 to 18:00, while water consumption rate was calculated from the ratio of water consumption to leaf area.

3.2.3 Soil water content

The soil water of potted seedlings was measured by TRIME-TDR in the process of measuring T_r.

3.2.4 Leaf area

Fresh leaf areas with different weights were measured by drainage, and a correlation between leaf weight and leaf area was established. The whole leaf area of seedlings was calculated with a harvest method. The leaf area of pine seedlings was calculated with the widely used formula for drainage as follows:

$$A = 2L(1+\pi/n)\sqrt{nV/\pi L}.$$

where A is leaf area (cm^2), V needle-leaved volume (cm^3), n the number of each pine needle bundle, and L the total length of the pine needle (cm).

3.2.5 Meteorological elements

Air temperature, air humidity, solar radiation, photosynthetically active radiation and solar radiation were observed by the HOBO weather station in 2004.

4 Results and analysis

4.1 Weather factors

The diurnal course of solar radiation (R_s), photosynthetically active radiation (*PAR*), air temperature (T_a) and air relative humidity (*RH*) are presented in Figs. 1 and 2. The curve of *PAR* showed a single-peak curve, where the maximum values of *PAR* were 2120, 2030 and 1606 μmol/(m^2·s) respectively at midday of the three dates; the maximum values of T_a appeared at 14:00 and were 25.8, 29.8 and 20.4°C respectively. *RH* showed a gradually descending trend from 69.4%, 77.5% and 70.3% at 8:00 to 42.9%, 65.5% and 24.8% at 14:00, then gradually increased to 57.4%, 85.7% and 44.2% at 18:00 on the typical clear days of July 8, August 3 and October 5, in 2004.

4.2 Water consumption rates of *P. tabulaeformis* seedlings

As seen in Fig. 3, water consumption rates of the seedlings clearly showed the diurnal course with a double-peaked

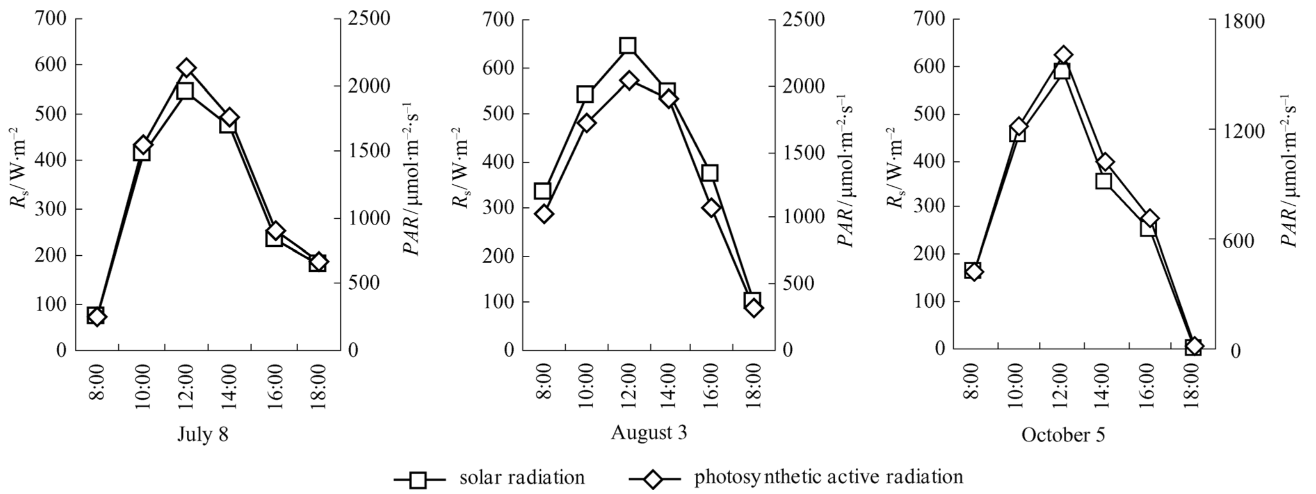

Fig. 1 Daily changes of solar radiation and photosynthetically active radiation

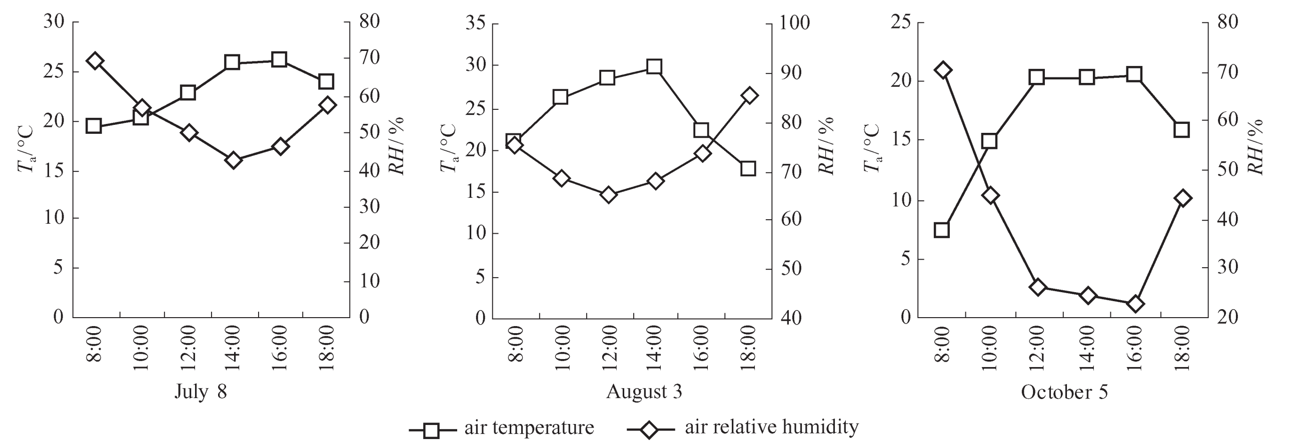

Fig. 2 Daily changes of air temperature and air relative humidity

curve trend. The maximum water consumption rate was 62 g/(m^2·h) at 12:00–14:00, with the average water consumption rates during day and night at 45.3 and 5.6 g/(m^2·h) respectively. The average daily water consumption rate was 8.09 times that at night. The average daily water consumption rate under light soil water stress condition was 39.5 g/(m^2·h) and declined to 12.7%. This was compared with the average daily water consumption rate under adequate soil water conditions. The average daily water consumption rate under severe soil water stress was 6.8 g/(m^2·h), decreasing 84.9% and obscuring the changing diurnal course with an approximately linear trend.

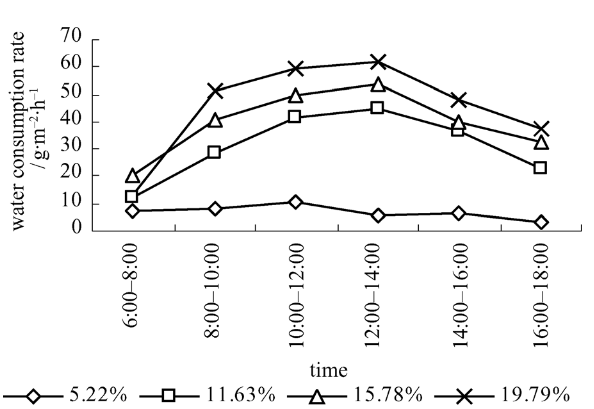

Fig. 3 Daily change of water consumption rate of *P. tabulaeformis* under different soil water contents

4.3 Transpiration rate and stomatal resistance of seedlings under different soil water conditions

As seen in Fig. 4, the diurnal course of T_r of the pine seedlings displayed a double-peaked curve under adequate soil water and light soil water stress. T_r showed two peaks, at 10:00 and 14:00 hours, which reached values of 1.80 and 1.94 mmol/(m^2·s) respectively. The average T_r of the day was 1.44 mmol/(m^2·s) on August 3. Under conditions of severe soil water stress, the T_r of *P. tabulaeformis* showed an increasing trend and reached a maximum value at 10:00, then displayed a declining trend and maintained a low value. The average T_r of the day was

0.29 mmol/(m^2·s). The average T_r of the day under adequate soil water was 4.96 greater than that of the day under severe drought. Therefore, pine seedlings showed a strong ability of controlling dehydration and maintaining hydrological balance and drought resistance.

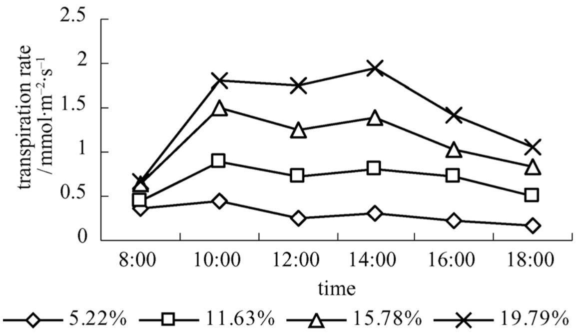

Fig. 4 Diurnal course of transpiration rate of *P. tabulaeformis*

The diurnal course of R_{st} was affected not only by its physiological mechanism, but also by environmental factors and displayed a "W" curve under different conditions of soil moisture. R_{st} reached a maximum value under severe drought conditions and declined with an increase of soil water content. The average R_{st} of the day were 14.81, 8.39, 5.98 and 4.25 s/cm respectively under conditions of adequate soil water, light soil water stress, medium soil water stress and severe soil water stress on August 3 (Fig. 5).

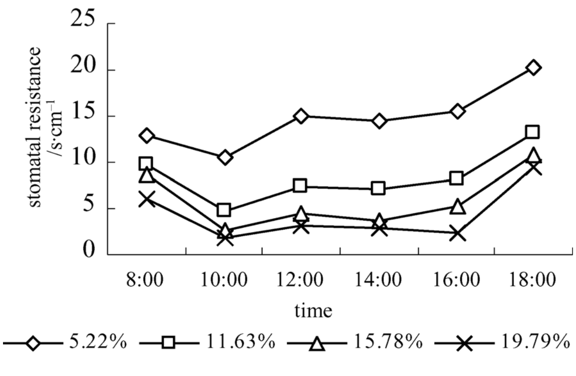

Fig. 5 Diurnal course of stomatal resistance of *Pinus tabulaeformis*

4.4 Relationship between transpiration rate and SWC

The transpiration rate of pine seedlings showed a markedly increasing trend, a slightly increasing trend and a declining trend with a continuous increase in soil water. The relation between T_r and *SWC* was analyzed statistically with SPSS:

$$y = ax^3 + bx^2 + cx + d$$

where y is transpiration rate (mmol/(m^2·s)); x is soil water content (%); and a, b, c, d are the parameters to be estimated.

$$dy/dx = 3ax^2 + 2bx + c$$

when $dy/dx = 0$, the value of *SWC* which maximizes T_r were 17.7%, 19.8% and 17.5% in July, August and October respectively.

Table 1 shows the *SWC* which maintained the maximum value of T_r between 17%–20%. The value of *SWC* which corresponded to the maximum value of T_r in July and August was higher than that in October.

4.5 Relationship between transpiration rate and meteorological factors

The relation between T_r and meteorological factors was analyzed by multiple linear regression methods. T_r was largely affected by tree physiological mechanisms and meteorological factors under adequate soil water conditions, but greatly affected by *SWC* under soil water stress (Shi et al., 2004). As shown in Table 2, T_r was significantly correlated with meteorological factors when soil water was sufficient, but would decrease under soil water stress conditions.

As shown in Table 3, the relationship between T_r and T_a, T_l, *PAR* showed a positive correlation, while the relationship between T_r and *RH* were negatively correlated. The correlation coefficient between T_a and T_r was maximum when T_a was the main factor affecting T_r in July and August and *PAR* in October under severe drought. The correlation coefficient between T_a and T_r was maximum when T_a was the main factor affecting T_r in July, T_l in August and October under light water stress conditions. When the soil water was sufficient, the correlation coefficient between *RH* and T_r was a maximum when the main factor affecting T_r was *RH*, T_a and T_l in August and October respectively.

5 Conclusions and discussion

Water consumption rates of the seedlings showed a clear diurnal course and displayed single-peak curves under adequate soil water, light water soil stress and medium water soil stress. The average water consumption rate of day and night was 45.3 and 5.6 g/(m^2·h) respectively, the average water consumption rate of the day was 8.09 times that of the night. The average water consumption rate of the day under light soil water stress condition decreased 12.7%, compared with the average water consumption rate of the day under adequate soil water conditions. The average water consumption rate of the day under conditions of severe soil water stress decreased 84.9%

Table 1 Statistical model of soil water content and evaporation rate of *P. tabulaeformis*

month	parameter				R^2	*df*	*F*	*SWC*/%
	a	*b*	*c*	*d*				
July	−0.0008	0.0181	0.1091	0.4085	0.746	36	21.51	17.7
August	−0.0009	0.0321	−0.2147	0.9601	0.919	36	98.74	19.8
October	−0.00004	−0.0047	0.2010	−0.6032	0.870	36	57.84	17.5

Table 2 Regression analysis of meteorological factors and transpiration rates of *P. tabulaeformis* in 2004

month	*SWC*/%	regression equation	R^2	*df*	*F*	*Sig.*
July	5–8	$T_r = -8.048 + 0.008\ PAR - 0.0069\ RH - 4.732\ T_l + 5.532\ T_a$	0.510	47	11.182	0.000
	13–16	$T_r = 0.273 + 0.009\ PAR - 0.091\ RH - 1.611\ T_l + 2.199\ T_a$	0.616	35	12.484	0.000
	18–21	$T_r = 5.946 + 0.0010\ PAR - 0.139\ RH - 1.403\ T_l + 1.924\ T_a$	0.697	71	38.686	0.000
August	5–8	$T_r = -4.868 + 0.000001 PAR + 0.028\ RH + 0.053\ T_l + 0.134\ T_a$	0.315	59	6.307	0.000
	13–16	$T_r = 2.035 + 0.002\ PAR - 0.020\ RH - 0.161\ T_l + 0.213\ T_a$	0.536	71	19.320	0.000
	18–21	$T_r = 3.436 + 0.002\ PAR - 0.060\ RH - 0.441\ T_l + 0.581\ T_a$	0.601	49	16.885	0.000
October	5–8	$T_r = -0.895 + 0.001\ PAR + 0.009\ RH - 0.350\ T_l + 0.222\ T_a$	0.268	45	3.761	0.011
	13–16	$T_r = 2.985 + 0.001\ PAR - 0.055\ RH + 0.257\ T_l - 0.229\ T_a$	0.436	47	8.306	0.000
	18–21	$T_r = 1.139 + 0.002\ PAR - 0.045\ RH + 0.224\ T_l - 0.106\ T_a$	0.745	83	57.856	0.000

Table 3 Correlation coefficients of transpiration rates and meteorological factors of *P. tabulaeformis* in 2004

month	*SWC*/%	*PAR*/μmol·m^{-2}·s^{-1}	*RH*/%	T_l/°C	T_a/°C
July	5–8	0.351*	−0.303*	0.247	0.357*
	13–16	0.402**	−0.602**	0.601**	0.605**
	18–21	0.526**	−0.734**	0.608**	0.596**
August	5–8	0.510**	−0.322*	0.471**	0.537**
	13–16	0.708**	−0.566**	0.770**	0.656**
	18–21	0.655**	−0.688**	0.696**	0.714**
October	5–8	0.427**	−0.279	0.351*	0.341*
	13–16	0.338**	−0.588**	0.620**	0.614**
	18–21	0.544**	−0.687**	0.799**	0.782**

Note: ** was significant difference ($\alpha = 0.01$); * was significant difference ($\alpha = 0.05$).

and obscured the diurnal course, with the descending trend becoming approximately linear.

The diurnal course of T_r and R_{st} displayed a double-peaked curve and a "W" curve respectively. The average T_r of the day was 1.44 and 0.29 mmol/(m^2·s) respectively under adequate soil water and severe water stress. The average T_r of the day under adequate soil water was 4.96 times that of the day under severe water stress. Stomatal resistance (R_{st}) reached a maximum value under severe drought conditions and declined with an increase of SWC. The average R_{st} of the day was 14.81, 8.39, 5.98 and 4.25 s/cm respectively under conditions of adequate soil water, light soil water stress, medium soil water stress and severe soil water stress.

The levels of *SWC* which maximized the value of T_r were 17.7%, 19.8% and 17.5% in July, August and October respectively and were maintained between 17%–20%.

The correlation coefficient between T_a and T_r was maximum when T_a was the main factor to affect T_r in July and August. The main factor affecting T_r was *PAR* in October under severe soil water stress conditions; when soil water is sufficient, the main factor affecting T_r was *RH*, T_a and T_l in August and October respectively.

Relationships between the transpiration rate of *P. tabulaeformis* and the factors affecting it were studied under a potting experiment. Due to a rather large difference between the natural environment of seedlings under a potting experiment and the natural environment of forest trees under field experiments, the difference led to different physiological reactions. Therefore, the difference between our research results of the potting experiment and the results of forest tree field experiments should be studied in the future.

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